AN-2097 LM3444 - 230VAC, 8W Isolated Flyback LED Driver

1 Introduction

This demonstration board highlights the performance of a LM3444 based Flyback LED driver solution that can be used to power a single LED string consisting of 4 to 10 series connected LEDs from an 180 V_{RMS} to 265 V_{RMS}, 50 Hz input power supply. The key performance characteristics under typical operating conditions are summarized in this application note.

This is a four-layer board using the bottom and top layer for component placement. The demonstration board can be modified to adjust the LED forward current, the number of series connected LEDs that are driven and the switching frequency. Refer to the LM3444 datasheet for detailed instructions.

A bill of materials is included that describes the parts used on this demonstration board. A schematic and layout have also been included along with measured performance characteristics.

2 Key Features

- Line injection circuitry enables PFC values greater than 0.98
- Adjustable LED current and switching frequency
- Flicker free operation

3 Applications

- Solid State Lighting
- Industrial and Commercial Lighting
- Residential Lighting

4 Performance Specifications

Based on an LED V_f = 3.6V

Symbol	Parameter	Min	Typ	Max
V_{IN}	Input voltage	180 V_{RMS}	230 V_{RMS}	265 V_{RMS}
V_{OUT}	LED string voltage	13 V	21.5 V	36 V
I_{LED}	LED string average current	-	350 mA	-
P_{OUT}	Output power	-	7.5 W	-
f_{sw}	Switching frequency	-	67 kHz	-

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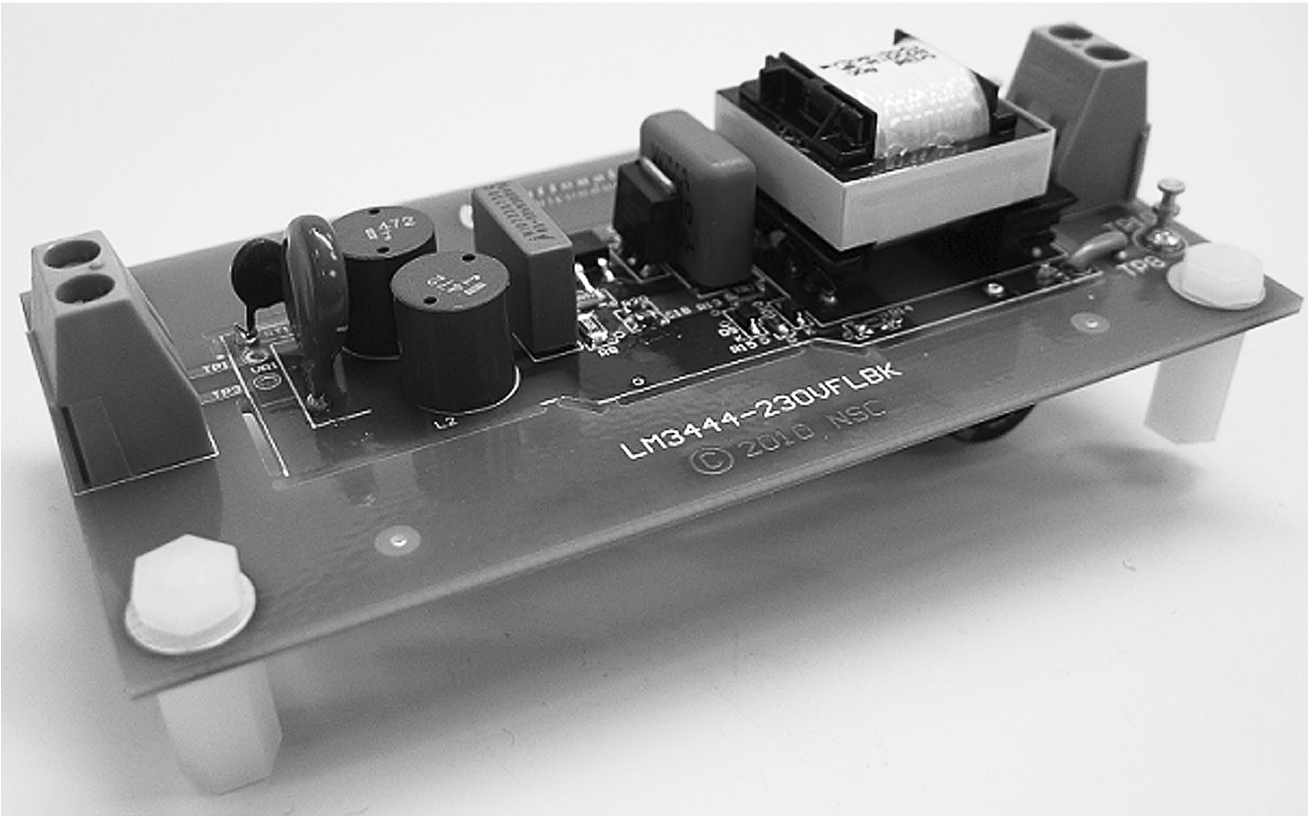
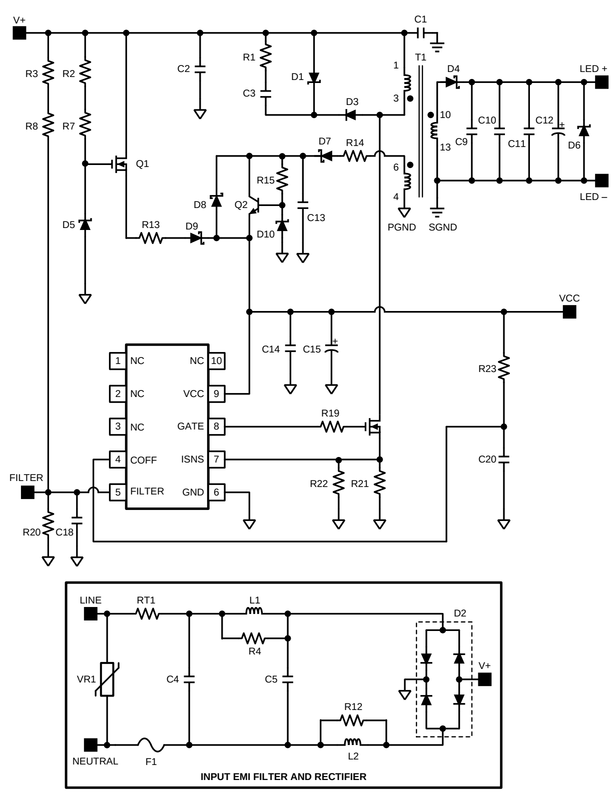
Figure 1. Demo Board



5 LM3444 230VAC, 8W Isolated Flyback LED Driver Demo Board Schematic



WARNING

The LM3444 evaluation board has exposed high voltage components that present a shock hazard. Caution must be taken when handling the evaluation board. Avoid touching the evaluation board and removing any cables while the evaluation board is operating.

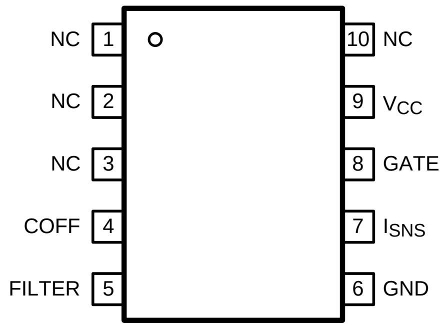
WARNING

The ground connection on the evaluation board is NOT referenced to earth ground. If an oscilloscope ground lead is connected to the evaluation board ground test point for analysis and the mains AC power is applied (without any isolation), the fuse (F1) will fail open. For bench evaluation, either the input AC power source or the bench measurement equipment should be isolated from the earth ground connection. Isolating the evaluation board (using 1:1 line isolation transformer) rather than the oscilloscope is highly recommended.

WARNING

The LM3444 evaluation board should not be powered with an open load. For proper operation, ensure that the desired number of LEDs are connected at the output before applying power to the evaluation board.

6 LM3444 Device Pin-Out



7 Pin Descriptions – 10 Pin VSSOP

Pin #	Name	Description
1	NC	No internal connection.
2	NC	No internal connection.
3	NC	No internal connection.
4	COFF	OFF time setting pin. A user set current and capacitor connected from the output to this pin sets the constant OFF time of the switching controller.
5	FILTER	Filter input. A capacitor tied to this pin filters the error amplifier. Could also be used as an analog dimming input.
6	GND	Circuit ground connection.
7	ISNS	LED current sense pin. Connect a resistor from main switching MOSFET source, ISNS to GND to set the maximum LED current.
8	GATE	Power MOSFET driver pin. This output provides the gate drive for the power switching MOSFET of the buck controller.
9	V_{CC}	Input voltage pin. This pin provides the power for the internal control circuitry and gate driver.
10	NC	No internal connection.

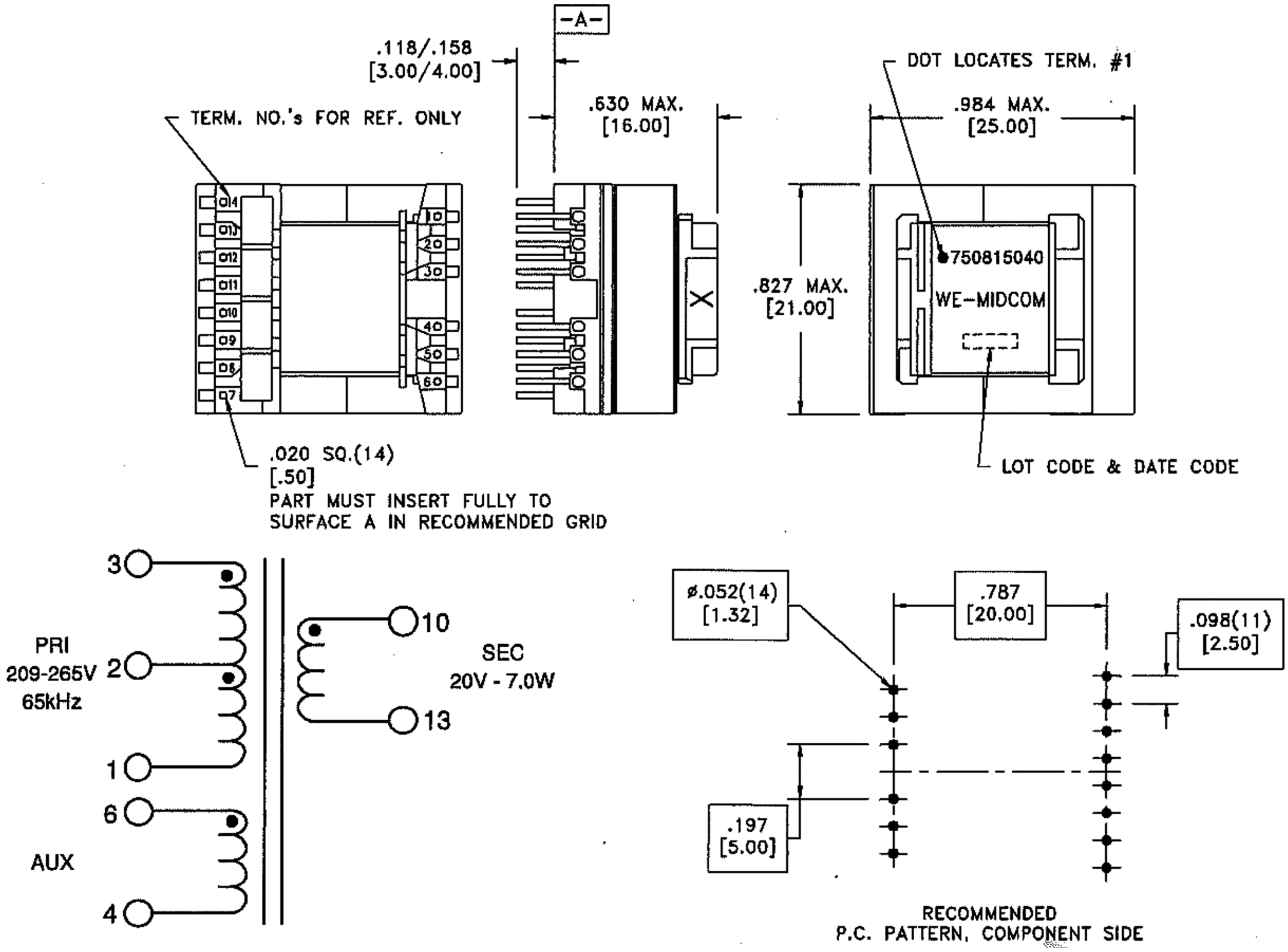
8 Bill of Materials

Designator	Description	Manufacturer	Part Number	RoHS
U1	Offline LED Driver, PowerWise™	Texas Instruments	LM3444	Y
C1	Ceramic, X7R, 250VAC, 10%	Murata Electronics North America	DE1E3KX332MA5BA01	Y
C2	Ceramic, Polypropylene, 400VDC, 10%	WIMA	MKP10-.033/400/5P10	Y
C3	CAP, CERM, 330pF, 630V, +/-5%, C0G/NP0, 1206	TDK	C3216C0G2J331J	Y
C4	Ceramic, X7R, 250V, X2, 10%, 2220	Murata Electronics North America	GA355DR7GF472KW01L	Y
C5	CAP, Film, 0.033µF, 630V, +/-10%, TH	EPCOS Inc	B32921C3333K	Y
C9, C11	CAP, CERM, 1µF, 50V, +/-10%, X7R, 1210	MuRata	GRM32RR71H105KA01L	Y
C10	CAP, CERM, 0.47µF, 50V, +/-10%, X7R, 0805	MuRata	GRM21BR71H474KA88L	Y
C12	Aluminium Electrolytic, 680uF, 35V, 20%,	Nichicon	UHE1V681MHD6	Y
C13	CAP, CERM, 1µF, 35V, +/-10%, X7R, 0805	Taiyo Yuden	GMK212B7105KG-T	Y
C14	CAP, CERM, 0.1µF, 25V, +/-10%, X7R, 0603	MuRata	GRM188R71E104KA01D	Y
C15	CAP, TANT, 47uF, 16V, +/-10%, 0.35 ohm, 6032-28 SMD	AVX	TPSC476K016R0350	Y
C18	CAP, CERM, 2200pF, 50V, +/-10%, X7R, 0603	MuRata	GRM188R71H222KA01D	Y
C20	CAP, CERM, 330pF, 50V, +/-5%, C0G/NP0, 0603	MuRata	GRM1885C1H331JA01D	Y
D1	DIODE TVS 250V 600W UNI 5% SMD	Littelfuse	P6SMB250A	Y

Designator	Description	Manufacturer	Part Number	RoHS
D2	Diode, Switching-Bridge, 600V, 0.8A, MiniDIP	Diodes Inc.	HD06-T	Y
D3	Diode, Silicon, 1000V, 1A, SOD-123	Comchip Technology	CGRM4007-G	Y
D4	Diode, Schottky, 100V, 1A, SMA	STMicroelectronics	STPS1H100A	Y
D5, D10	Diode, Zener, 13V, 200mW, SOD-323	Diodes Inc	DDZ13BS-7	Y
D6	Diode, Zener, 36V, 550mW, SMB	ON Semiconductor	1SMB5938BT3G	Y
D7, D8, D9	Diode, Schottky, 100V, 150 mA, SOD-323	STMicroelectronics	BAT46JFILM	Y
F1	Fuse, 500mA, 250V, Time-Lag, SMT	Littelfuse Inc	0443.500DR	Y
H1, H2, H5, H6	Standoff, Hex, 0.5"L #4-40 Nylon	Keystone	1902C	Y
H3, H4, H7, H8	Machine Screw, Round, #4-40 x 1/4, Nylon, Philips panhead	B&F Fastener Supply	NY PMS 440 0025 PH	Y
J1, J2	Conn Term Block, 2POS, 5.08mm PCB	Phoenix Contact	1715721	Y
L1, L2	Inductor, Radial Lead Inductors, Shielded, 4.7mH, 130mA, 12.20ohm, 7.5mm Radial,	TDK Corporation	TSL080RA-472JR13-PF	Y
LED+, LED-, TP7, TP8	Terminal, 22 Gauge Wire, Terminal, 22 Guage Wire	3M	923345-02-C	Y
Q1	MOSFET, N-CH, 600V, 200mA, SOT-223	Fairchild Semiconductor	FQT1N60CTF_WS	Y
Q2	Transistor, NPN, 300V, 500mA, SOT-23	Diodes Inc.	MMBTA42-7-F	Y
Q3	MOSFET, N-CH, 650V, 800mA, IPAK	Infineon Technologies	SPU01N60C3	Y
R1	RES, 221 ohm, 1%, 0.25W, 1206	Vishay-Dale	CRCW1206221RFKEA	Y
R2, R7	RES, 200k ohm, 1%, 0.25W, 1206	Vishay-Dale	CRCW1206200KFKEA	Y
R3, R8	RES, 309k ohm, 1%, 0.25W, 1206	Vishay-Dale	CRCW1206309KFKEA	Y
R4, R12	RES, 10k ohm, 5%, 0.25W, 1206	Vishay-Dale	CRCW120610K0JNEA	Y
R13	RES, 33.0 ohm, 1%, 0.25W, 1206	Vishay-Dale	CRCW120633R0FKEA	Y
R14	RES, 10 ohm, 5%, 0.125W, 0805	Vishay-Dale	CRCW080510R0JNEA	Y
R15	RES, 10.0k ohm, 1%, 0.1W, 0603	Vishay-Dale	CRCW060310K0FKEA	Y
R19	RES, 10 ohm, 5%, 0.1W, 0603	Vishay-Dale	CRCW060310R0JNEA	Y
R20	RES, 1.91k ohm, 1%, 0.1W, 0603	Vishay-Dale	CRCW06031K91FKEA	Y
R21	RES, 2.70 ohm, 1%, 0.25W, 1206	Panasonic	ERJ-8RQF2R7V	Y
R22	RES, 10.7 ohm, 1%, 0.125W, 0805	Vishay-Dale	CRCW080510R7FKEA	Y
R23	RES, 324k ohm, 1%, 0.1W, 0603	Vishay-Dale	CRCW0603324KFKEA	Y
RT1	Current Limitor Inrush, 60Ohm, 20%, 5mm Raidal	Cantherm	MF72-060D5	Y
T1	FLBK TFR, 2.07 mH, Np=140T, Ns=26T, Na= 20T	Wurth Elektornik	750815040 REV 1	Y
TP9, TP10	Terminal, Turret, TH, Double	Keystone Electronics	1502-2	Y
VR1	Varistor 275V 55J 10mm DISC	EPCOS Inc	S10K275E2	Y

9 Transformer Design

Mfg: Wurth Electronics, Part #: 750815040 Rev. 01



Parameter	Test Conditions	Value
D.C. Resistance (3-1)	20°C	1.91 Ω ± 10%
D.C. Resistance (6-4)	20°C	0.36 Ω ± 10%
D.C. Resistance (10-13)	20°C	0.12 Ω ± 10%
Inductance (3-1)	10 kHz, 100 mVAC	2.12 mH ± 10%
Inductance (6-4)	10 kHz, 100 mVAC	46.50 µH ± 10%
Inductance (10-13)	10 kHz, 100 mVAC	74.00 µH ± 10%
Leakage Inductance (3-1)	100 kHz, 100 mAVAC (tie 6+4, 10+13)	18.0 µH Typ., 22.60 µH Max.
Dielectric (1-13)	tie (3+4), 4500 VAC, 1 second	4500 VAC, 1 minute
Turns Ratio	(3-1):(6-4)	7:1 ± 1%
Turns Ratio	(3-1):(10:13)	5.384:1 ± 1%

10 Demo Board Wiring Overview

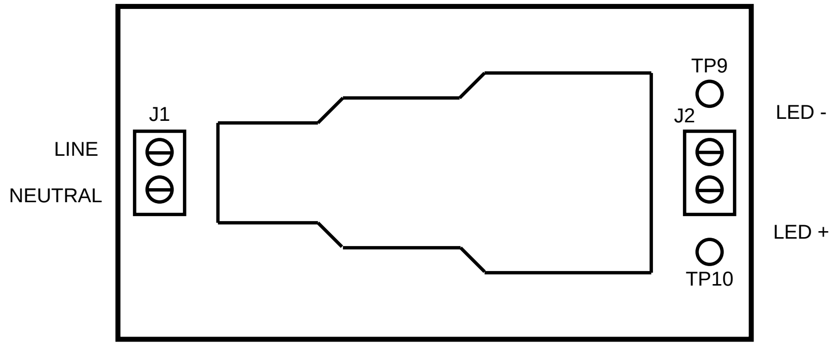


Figure 2. Wiring Connection Diagram

Test Point	Name	I/O	Description
TP10, J2-1	LED +	Output	**LED Constant Current Supply** Supplies voltage and constant-current to anode of LED string.
TP9, J2-2	LED -	Output	**LED Return Connection (not GND)** Connects to cathode of LED string. Do NOT connect to GND.
J1-1	LINE	Input	**AC Line Voltage** Connects directly to AC line of a 230VAC system.
J1-2	NEUTRAL	Input	**AC Neutral** Connects directly to AC neutral of a 230VAC system.

11 Demo Board Assembly

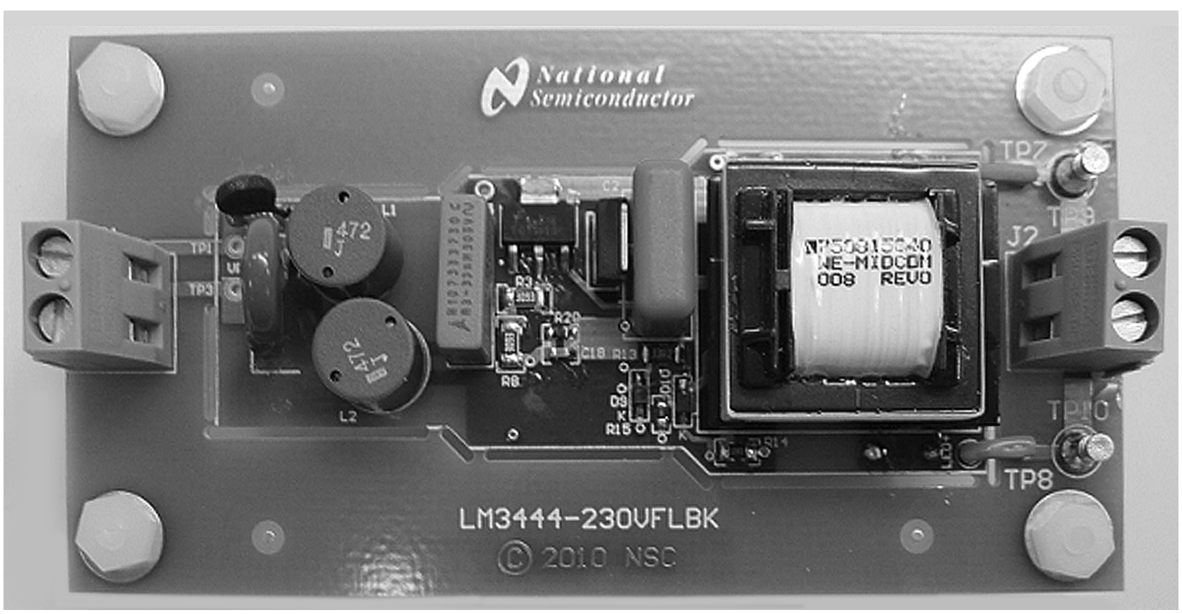


Figure 3. Top View

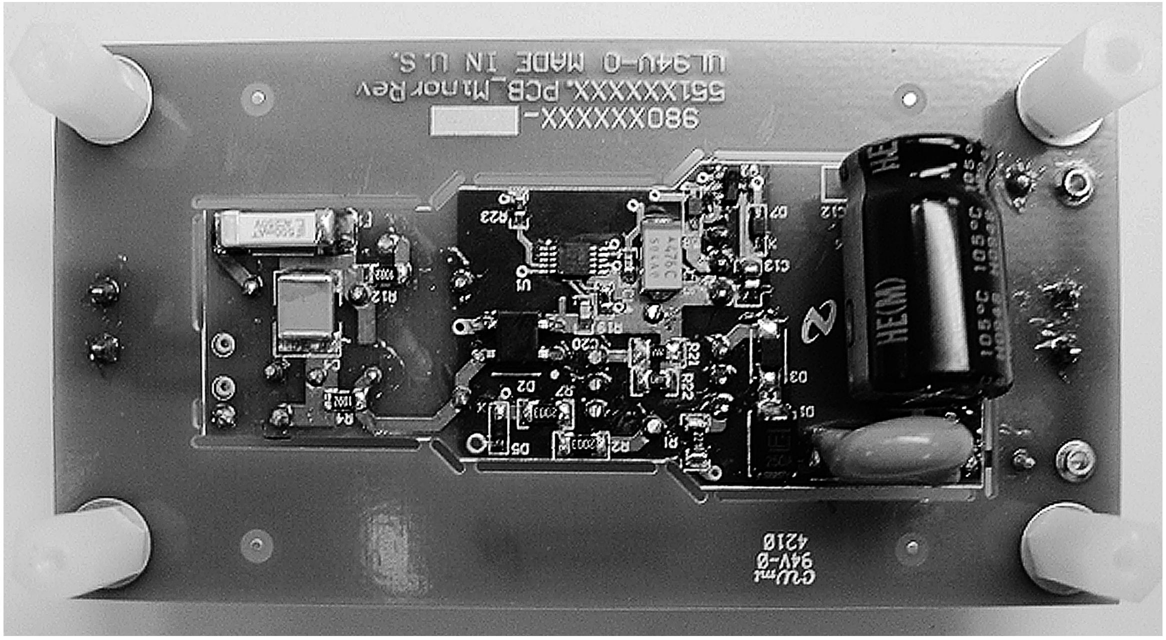


Figure 4. Bottom View

12 Typical Performance Characteristics

Original Circuit (6 LEDs operating at 350mA): R21 = 2.7Ω; Modification A (10 LEDs operating at 375mA): R21 = 1.8Ω; Modification B (8 LEDs operating at 350mA): R21 = 2.2Ω; Modification C (4 LEDs operating at 315mA): R21 = 3.9Ω

The output power can be varied to achieve desired LED current by interpolating R21 values between the maximum of 3.9 Ω and minimum of 1.8 Ω

The maximum output voltage is clamped to 36 V. For operating LED string voltage > 36 V, replace D6 with suitable alternative

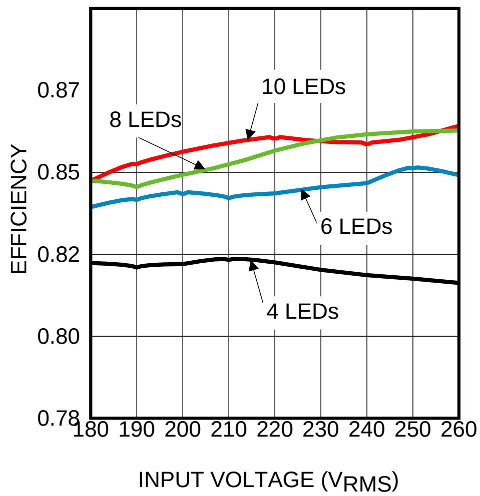


Figure 5. Efficiency vs. Line Voltage Original Circuit

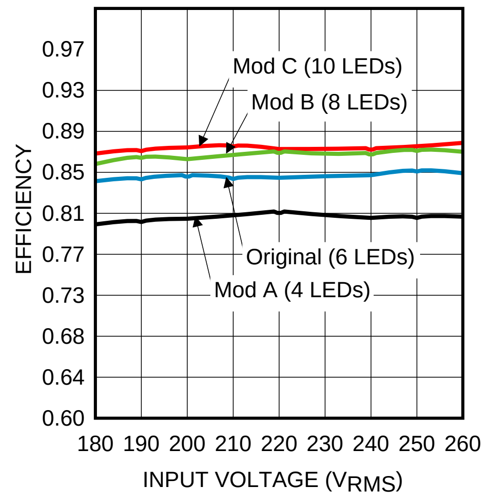


Figure 6. Efficiency vs. Line Voltage Modified Circuits

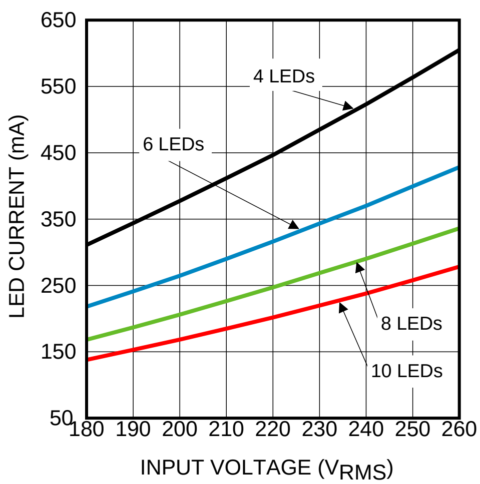


Figure 7. LED Current vs. Line Voltage Original Circuit

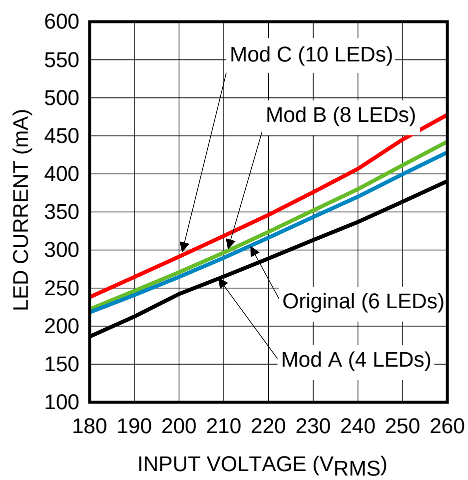


Figure 8. LED Current vs. Line Voltage Modified Circuits

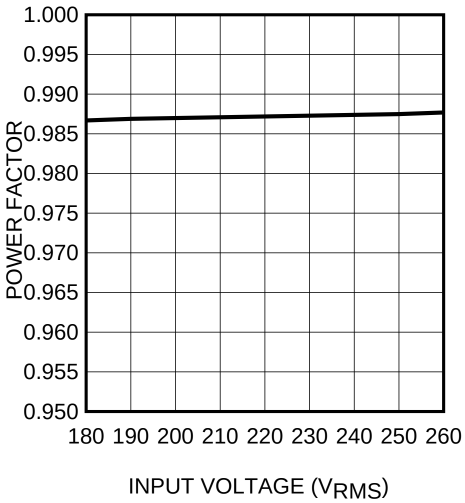


Figure 9. Power Factor vs. Line Voltage

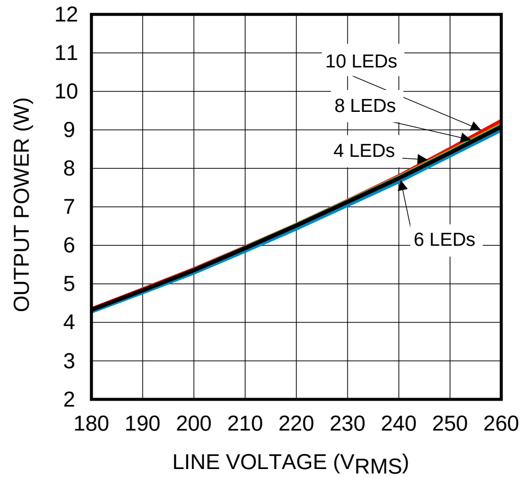


Figure 10. Output Power vs. Line Voltage Original Circuit

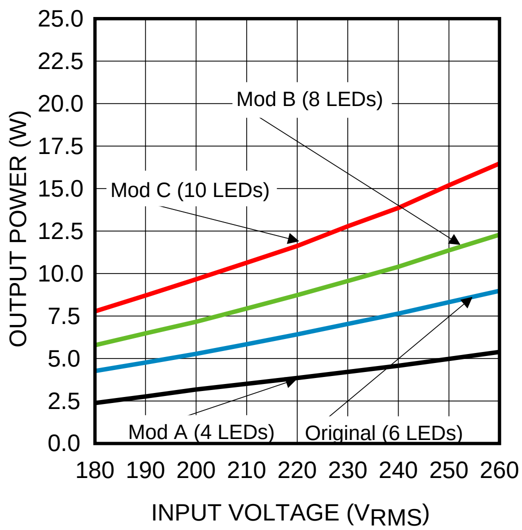


Figure 11. Output Power vs. Line Voltage Modified Circuits

Line Voltage and Line Current (V_{IN} = 230V_{RMS}, 6 LEDs, I_{LED} = 350mA)

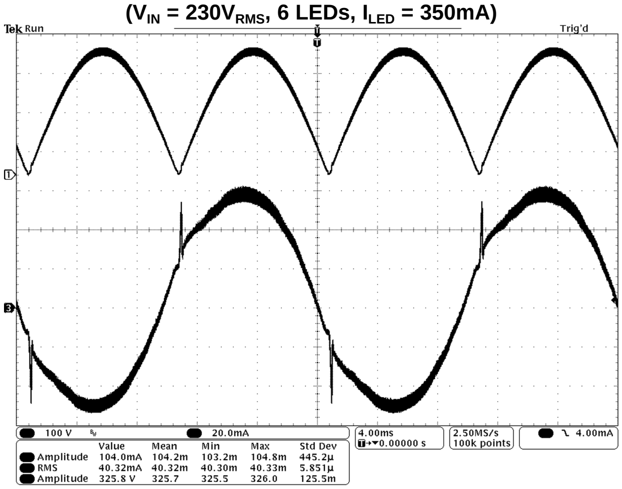


Figure 12. Ch1: Line Voltage (100 V/div); Ch3: Line Current (20 mA/div); Time (4 ms/div)

Output Voltage and LED Current (V_{IN} = 230V_{RMS}, 6 LEDs, I_{LED} = 350mA)

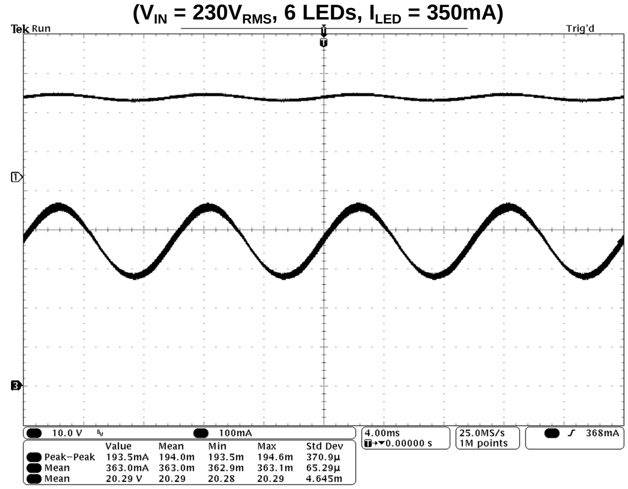


Figure 13. Ch1: Output Voltage (10 V/div); Ch3: LED Current (100 mA/div); Time (4 ms/div)

Power MOSFET Drain and ISNS (Pin-7) Voltage (V_{IN} = 230V_{RMS}, 6 LEDs, I_{LED} = 350mA)

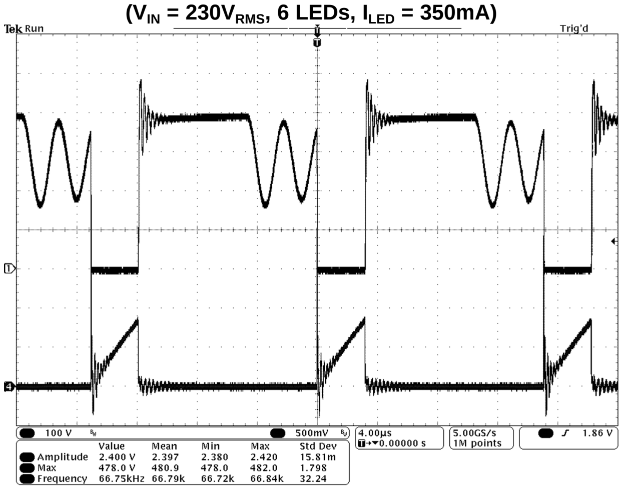


Figure 14. Ch1: Drain Voltage (100V/div); Ch4: ISNS Voltage (500 mV/div); Time (4 µs/div)

FILTER (Pin-5) and ISNS (Pin-7) Voltage (V_{IN}=230V_{RMS}, 6 LEDs, I_{LED} = 350mA

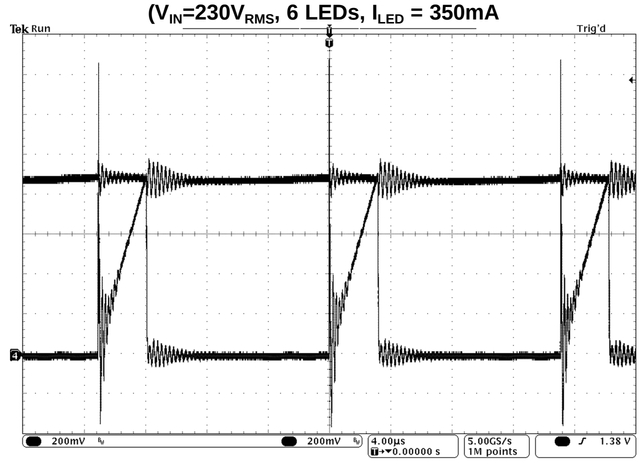


Figure 15. Ch1: FILTER Voltage (200 mV/div); ISNS Voltage (200 mV/div); Time (4 µs/div)

13 PCB Layout

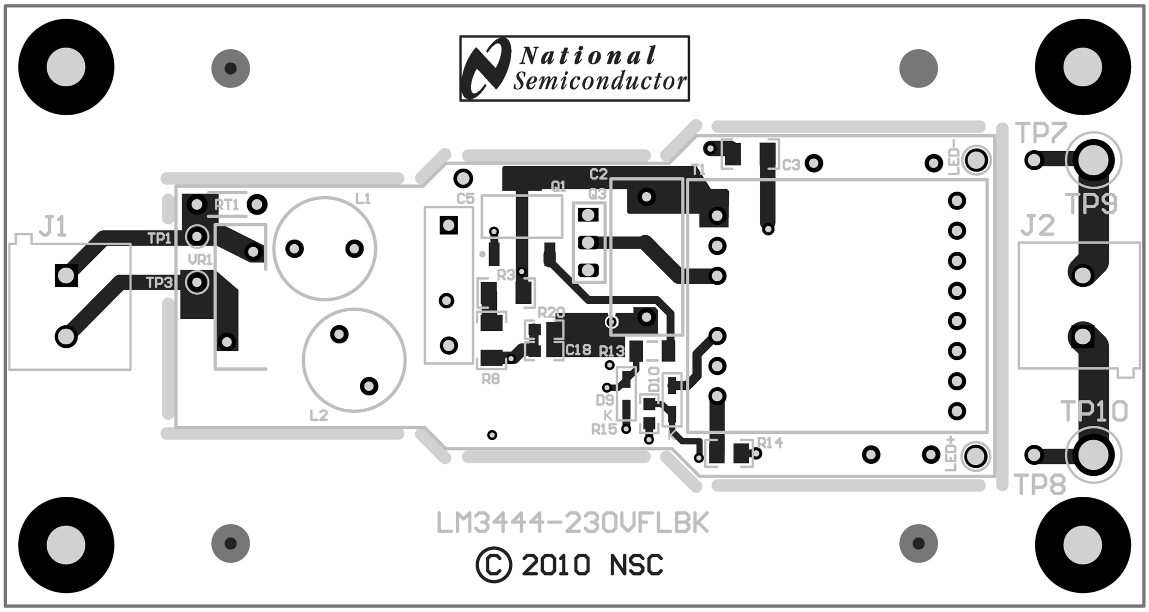


Figure 16. Top Layer

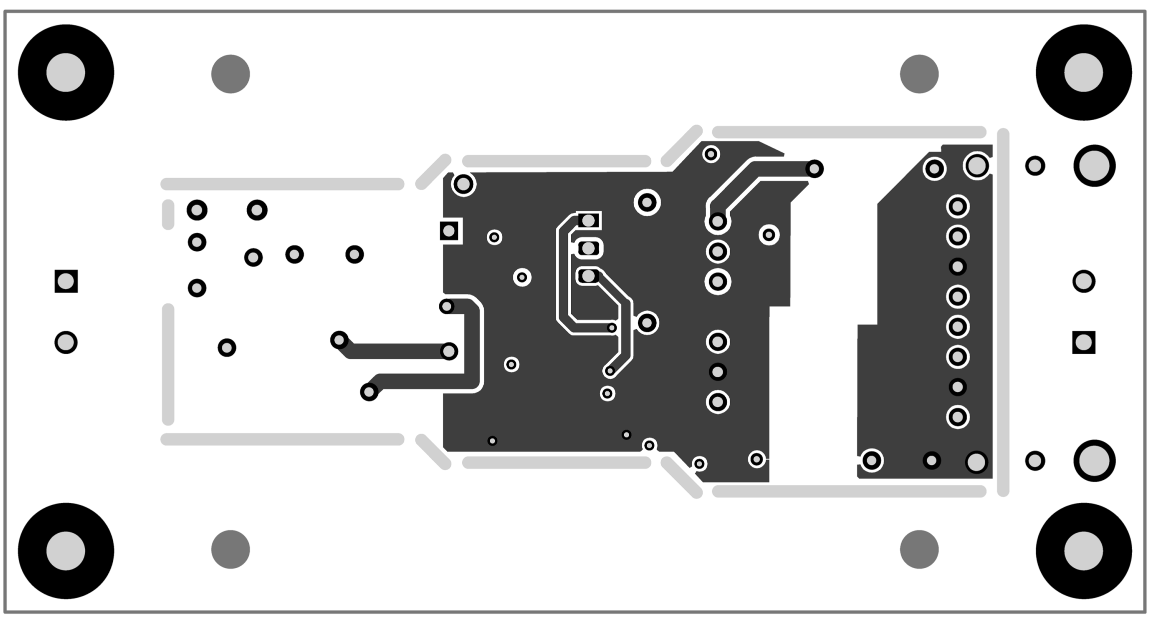


Figure 17. Top Middle Layer

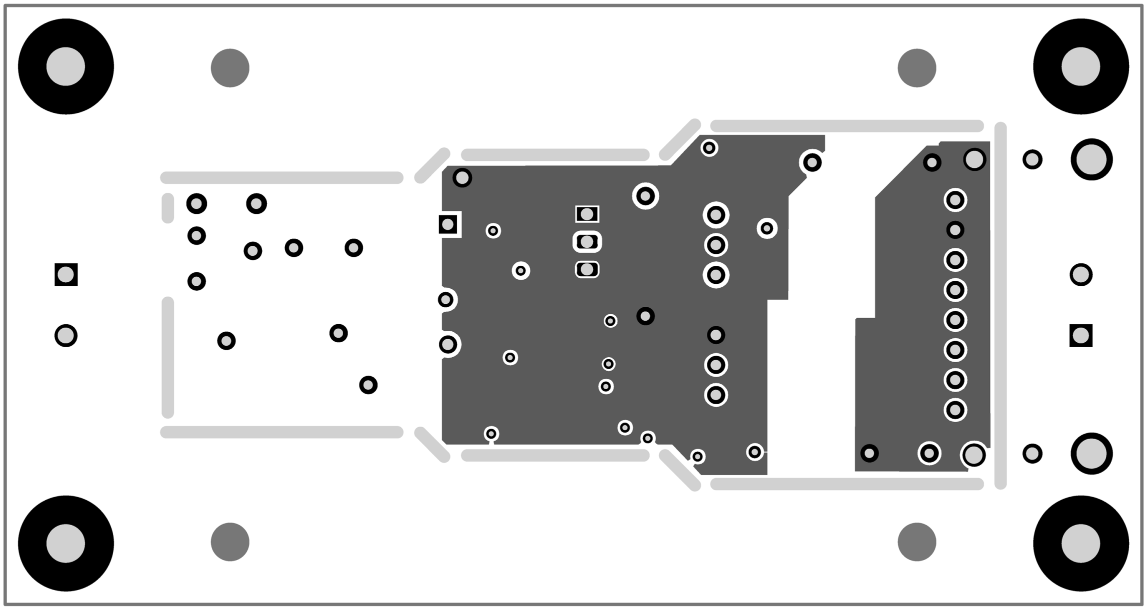


Figure 18. Bottom Middle Layer

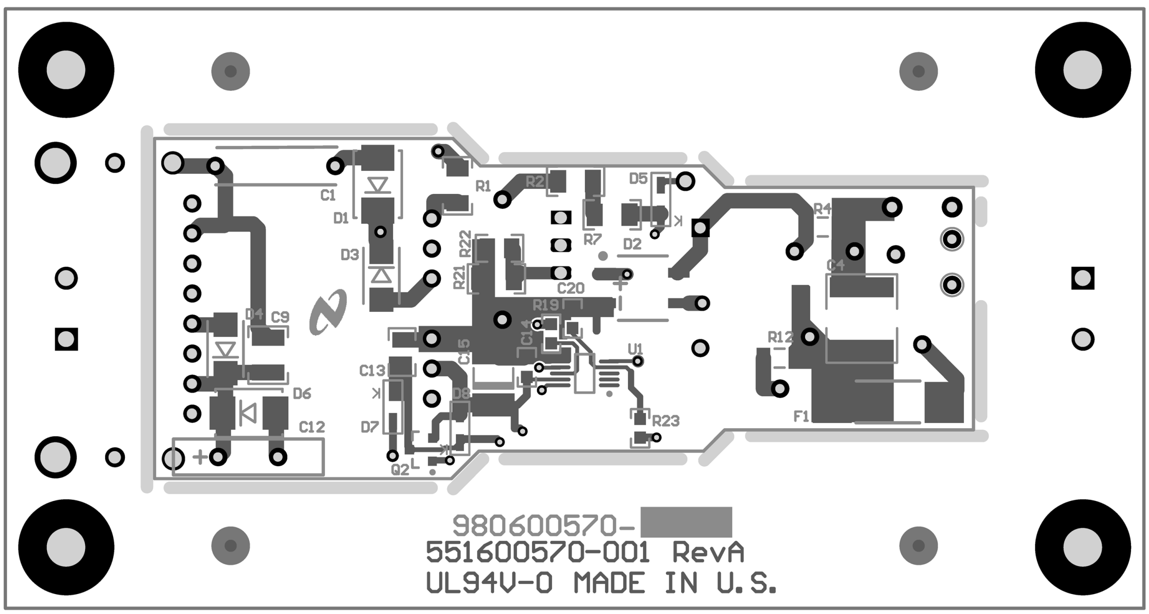


Figure 19. Bottom Layer

14 Experimental Results

The LED driver is designed to accurately emulate an incandescent light bulb and therefore behave as an emulated resistor. The resistor value is determined based on the LED string configuration and the desired output power. The circuit then operates in open-loop, with a fixed duty cycle based on a constant on-time and constant off-time that is set by selecting appropriate circuit components.

14.1 Performance

In steady state, the LED string voltage is measured to be 21.55 V and the average LED current is measured as 347.5 mA. The 100 Hz current ripple flowing through the LED string was measured to be 194 $mA_{pk\text{-}pk}$ at full load. The magnitude of the ripple is a function of the value of energy storage capacitors connected across the output. The ripple current can be reduced by increasing the value of energy storage capacitor or by increasing the LED string voltage.

The LED driver switching frequency is measured to be close to the specified 67 kHz. The circuit operates with a constant duty cycle of 0.21 and consumes near 9W of input power. The driver steady state performance for an LED string consisting of 6 series LEDs is summarized in the following table.

Table 1. Measured Efficiency and Line Regulation (6 LEDS)

V_{IN} (V_{RMS})	I_{IN} (mA_{RMS})	P_{IN}(W)	V_{OUT} (V)	I_{LED} (mA)	P_{OUT} (W)	Efficiency (%)	Power Factor
180	30.65	5.42	20.59	219.40	4.52	83.3	0.9867
190	32.35	6.06	20.80	242.55	5.05	83.3	0.9869
200	34.21	6.75	21.00	267.37	5.62	83.2	0.9870
210	36.01	7.47	21.18	293.39	6.21	83.2	0.9871
220	37.74	8.20	21.37	320.18	6.84	83.3	0.9872
230	39.44	8.96	21.55	347.51	7.49	83.6	0.9873
240	41.22	9.76	21.72	375.52	8.15	83.6	0.9874
250	43..29	10.62	21.90	404.82	8.86	83.5	0.9875
260	45.06	11.57	22.07	436.75	9.64	83.3	0.9877

14.2 Current THD

The LED driver is able to achieve close to unity power factor (PF ~ 0.98) which meets Energy Star requirements. This design also exhibits low current harmonics as a percentage of the fundamental current (as shown in the following table) and therefore meets the requirements of the IEC 61000-3-2 Class-3 standard. Total harmonic distortion was measured to be less than 1.2%.

Table 2. Measured Harmonic Current

Harmonic	Class C Limit (mA)	Measured (mA)
2	0.78	0.022
3	11.61	0.125
5	3.90	0.11
7	2.73	0.105
9	1.95	0.11
11	1.73	0.15
13	1.73	0.093
15	1.73	0.071
17	1.73	0.154
19	1.73	0.165
21	1.73	0.065
23	1.73	0.065
25	1.73	0.08
27	1.73	0.084
29	1.73	0.065
31	1.73	0.07

15 Electromagnetic Interference (EMI)

The EMI input filter of this evaluation board is configured as shown in the following circuit diagram.

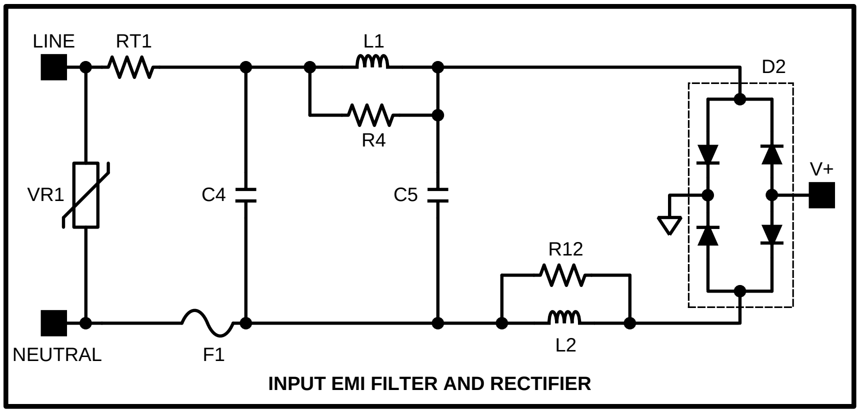
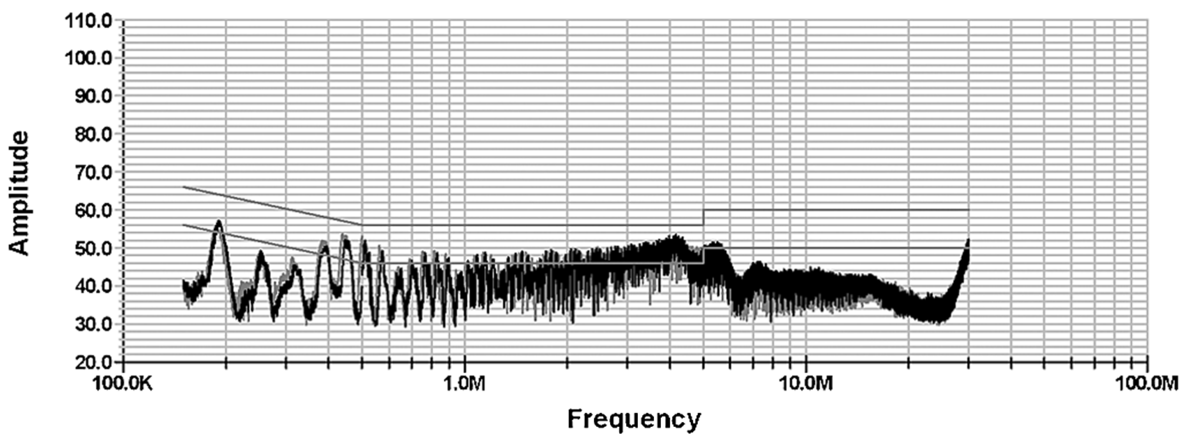


Figure 20. Input EMI Filter and Rectifier Circuit

In order to get a quick estimate of the EMI filter performance, only the PEAK conductive EMI scan was measured and the data was compared to the Class B conducted EMI limits published in FCC – 47, section 15.



CISPR 15 compliance pending

Figure 21. Peak Conductive EMI scan per CISPR-22, Class B Limits

16 Thermal Analysis

The board temperature was measured using an IR camera (HIS-3000, Wahl) while running under the following conditions:

V_{IN} = 230 V_{RMS}

I_{LED} = 348 mA

# of LEDs = 6

P_{OUT} = 7.2 W

The results are shown in the following figures.

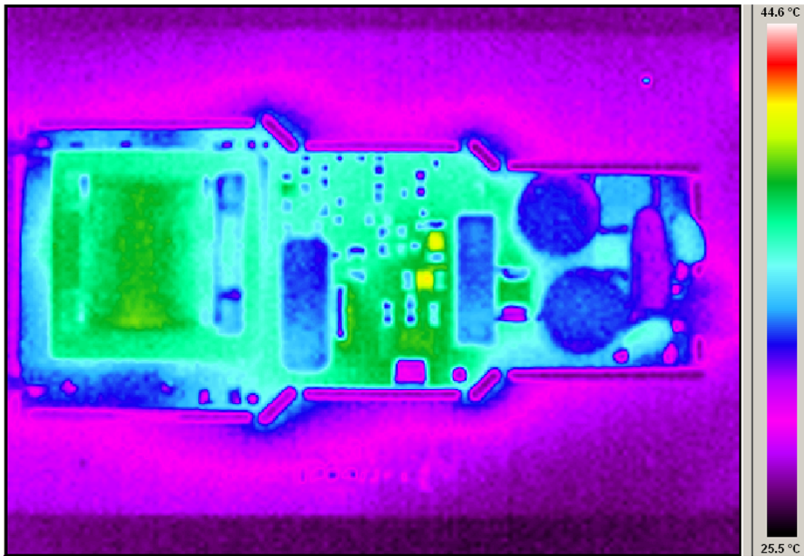


Figure 22. Top Side Thermal Scan

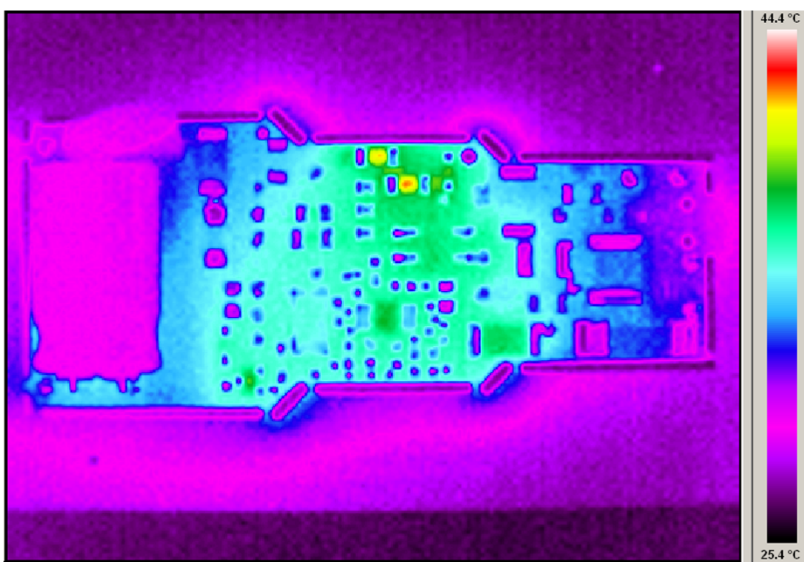


Figure 23. Bottom Side Thermal Scan

17 Circuit Analysis and Explanations

17.1 Injecting Line Voltage Into Filter (Achieving PFC > 0.98)

If a small portion (750mV to 1.00V) of line voltage is injected at FILTER of the LM3444, the circuit is essentially turned into a constant power flyback as shown in Figure 24.

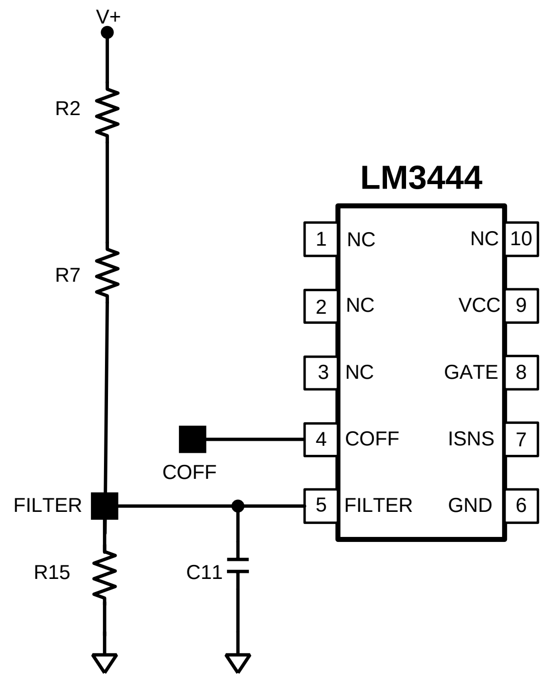


Figure 24. Line Voltage Injection Circuit

The LM3444 works as a constant off-time controller normally, but by injecting the 1.0V rectified AC voltage into the FILTER pin, the on-time can be made to be constant. With a DCM Flyback, Δi needs to increase as the input voltage line increases. Therefore$_{Pk}$ a constant on-time (since inductor L is constant) can be obtained.

By using the line voltage injection technique, the FILTER pin has the voltage wave shape shown in Figure 25 on it. Voltage at V_{FILTER} peak should be kept below 1.25V. At 1.25V current limit is tripped. C11 is small enough not to distort the AC signal but adds a little filtering.

Although the on-time is probably never truly constant, it can be observed in Figure 26 how (by adding the rectified voltage) the on-time is adjusted.

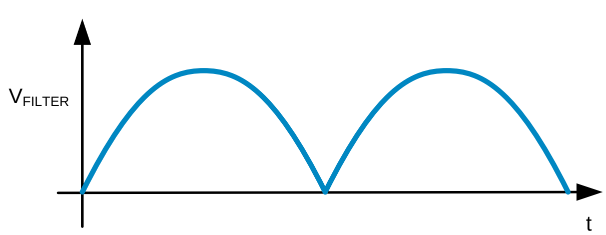


Figure 25. FILTER Waveform

For this evaluation board, the following resistor values are used:

R3 = R8 = 309 kΩ

R20 = 1.91 kΩ

Therefore the voltages observed on the FILTER pin will be as follows for listed input voltages:

For VIN = $180V_{RMS}$, $V_{FILTER,\ Pk}$ = 0.78V

For VIN = $230V_{RMS}$, $V_{FILTER,\ Pk}$ = 1.00V

For VIN = $265V_{RMS}$, $V_{FILTER,\ Pk}$ = 1.15V

Using this technique, a power factor greater than 0.98 can be achieved without additional passive active power factor control (PFC) circuitry.

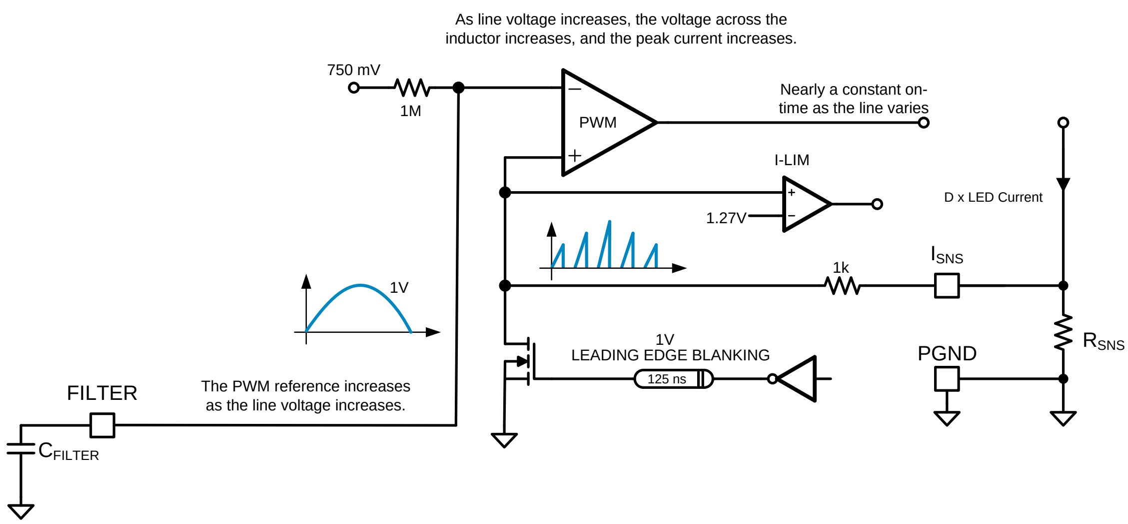


Figure 26. Typical Operation of FILTER Pin